

# On the origin of the system PSR B 1757–24/SNR G 5.4–1.2

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**Abstract.** A scenario for the origin of the system PSR B 1757–24/supernova remnant (SNR) G 5.4–1.2 is proposed. It is suggested that both objects are the remnants of a supernova (SN) that exploded within a pre-existing bubble blown-up by a runaway massive star (the SN progenitor) during the final (Wolf-Rayet) phase of its evolution. This suggestion implies that (a) the SN blast centre was significantly offset from the geometric centre of the wind-blown bubble (i.e. from the centre of the future SNR), (b) the bubble was surrounded by a massive wind-driven shell, and (c) the SN blast wave was drastically decelerated by the interaction with the shell. Therefore, one can understand how the relatively young and low-velocity pulsar PSR B 1757–24 was able to escape from the associated SNR G 5.4–1.2 and why the inferred vector of pulsar transverse velocity does not point away from the geometric centre of the SNR. A possible origin of the radio source G 5.27–0.9 (located between PSR B 1757–24 and the SNR G 5.4–1.2) is proposed. It is suggested that G 5.27–0.9 is a lobe of a low Mach number ( $\simeq 1.7$ ) jet of gas outflowing from the interior of G 5.4–1.2 through the hole bored in the SNR’s shell by the escaping pulsar. It is also suggested that the non-thermal emission of the comet-shaped pulsar wind nebula originates in the vicinity of the termination shock and in the cylindric region of subsonically moving shocked pulsar wind. The role of magnetized wind-driven shells (swept-up during the Wolf-Rayet phase from the ambient interstellar medium with the regular magnetic field) in formation of elongated axisymmetric SNRs is discussed.

**Key words.** Pulsars: individual: PSR B 1757–24 – ISM: bubbles – ISM: individual objects: G 5.4–1.2 – ISM: supernova remnants

## 1. Introduction

The pulsar PSR B 1757–24 is one of a growing number of neutron stars associated with SNRs. Although this radio pulsar was found well outside the shell of the SNR G 5.4–1.2 (Manchester et al. 1985), until recently there was no doubt about their physical association (Frail & Kulkarni 1991, Manchester et al. 1991). The high-resolution VLA image presented by Frail & Kulkarni (1991) shows a comet-shaped flat-spectrum nebula stretched behind the pulsar towards G 5.4–1.2. This nebula was interpreted as a ram-pressure-confined pulsar wind nebula, whose elongated morphology is due to the high-velocity motion of the pulsar through the interstellar medium.

Assuming that the pulsar was born in the apparent (geometric) centre of G 5.4–1.2 and that the true age of the pulsar,  $t_p$ , is equal to its characteristic spin-down age,

$\tau = P/2\dot{P} = 1.55 \times 10^4$  yr, where  $P = 125$  ms and  $\dot{P} = 1.28 \times 10^{-13}$  s s<sup>−1</sup> are, respectively, the spin period and the period derivative, Frail & Kulkarni (1991; see also Manchester et al. 1991) estimated the transverse velocity of the pulsar,  $v_p \geq 1900 d_5$  km s<sup>−1</sup>, where  $d_5$  is the distance to the system in units of 5 kpc (see Sect. 2).

The above estimate could be somewhat reduced if the SN exploded in a density-stratified medium: in this case, the actual SN explosion site does not coincide with the geometric centre of the SNR, but is shifted towards the high-density region (e.g. Gulliford 1974). The offset is significant only if the characteristic scale of the stratification is a small fraction of the radius of the SNR. In this case the SNR’s shell acquires a considerable elongation. The elongation of the SNR G 5.4–1.2, however, is moderate. Frail et al. (1994) used the Kompaneets (?) solution for a strong explosion in an exponentially-stratified medium to fit the shape of G 5.4–1.2 and found that the latter is consistent with the shape of a blast wave expanding into the medium with the exponential scale height less than

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one third of the diameter of the SNR. The model presented by Frail et al. (1994) allowed them to explain the “incorrect” orientation of the inferred line of pulsar proper motion (the comet-shaped nebula produced by the moving pulsar does not point back to the geometric centre of G 5.4–1.2) and to show that the SN blast centre could be offset towards the present position of PSR B 1757–24 by up to about a half of the radius of the SNR. The pulsar transverse velocity implied by the new possible location of the SN blast centre is  $\simeq 1400 d_5 \text{ km s}^{-1}$ , that corresponds to the pulsar proper motion of  $\mu \simeq 60 \text{ mas yr}^{-1}$  (Frail et al. 1994).

Subsequent observations of the pulsar wind nebula separated by a 6.7 yr period did not show any appreciable changes in its structure, putting a  $5\sigma$  upper limit on the pulsar westward proper motion and the transverse velocity, respectively,  $\mu \leq 25 \text{ mas yr}^{-1}$  and  $v_p \leq 590 d_5 \text{ km s}^{-1}$  (Gaensler & Frail 2000). The discrepancy between the “measured” transverse velocity and the implied one is even greater if one adopts a  $2\sigma$  upper limit on the westward pulsar motion derived by Thorsett et al. (2002) by combining their interferometric proper motion measurements of PSR B 1757–24 with the data taken from Gaensler & Frail (2000),  $\mu \leq 6.8 \text{ mas yr}^{-1}$ , or

$$v_p \leq v_p^{\text{max}} = 160 d_5 \text{ km s}^{-1}. \quad (1)$$

Thorsett et al. (2002) interpreted this discrepancy as an indication of an equally large discrepancy between the kinematic age of the system,  $t_{\text{kin}} = R_p/v_p$ , where  $R_p$  is the distance traveled by the pulsar from its birth-place, and the characteristic age of the pulsar (cf. Gaensler & Frail 2000). The latter discrepancy constitutes one of two arguments proposed by Thorsett et al. against the physical association between PSR B 1757–24 and the SNR G 5.4–1.2. The second argument against the association is the “incorrect” orientation of the implied pulsar proper motion. Thorsett et al. pointed out that a sharp density gradient across the SNR [required by the model of G 5.4–1.2 by Frail et al. (1994)] “without local inhomogeneities that disturb the circular symmetry seems daunting”, and concluded that the (implied) proper motion direction is “a serious problem for the association hypothesis”.

In this paper we propose a scenario for the origin of the system PSR B 1757–24/SNR G 5.4–1.2 based on the idea that both objects are the remnants of a cavity SN explosion of a moving massive star. In this case, the offset of the SN blast centre from the geometric centre of G 5.4–1.2 could be maximum (i.e. comparable with the radius of the SNR) even if the ambient interstellar medium is homogeneous (Gvaramadze 2002a,b; cf. Gvaramadze & Vikhlinin 2003, Gvaramadze 2003). Our scenario implies a much lower kinematic age of the system and naturally explains the orientation of the comet-shaped pulsar wind nebula. In Sect. 2 we review the relevant observational data on the system PSR B 1757–24/SNR G 5.4–1.2, while Sect. 3 contains a scenario for its origin. Sect. 4 deals with some

issues related to the content of the paper. Sect. 5 summarizes the work.

## 2. System PSR B 1757–24/SNR G 5.4–1.2: observational data

The 327 MHz image of the SNR G 5.4–1.2 by Frail et al. (1994) shows a nearly circular region of diffuse emission (of radius of  $15''.5$ ), bounded from the west side by a limb-brightened wing facing the Galactic plane. There are also indications of a weaker and more amorphous east wing. Both wings protrude in the north-south direction well beyond the area of diffuse emission and remind the flanks of a barrel-like SNR (see Sect. 3.2 and Sect. 4), so that the general structure of the SNR is elongated rather than circular. The elongated (barrel-like) structure of G 5.4–1.2 could also be derived from the polarization observations of this SNR: Milne et al. (1992) found that the magnetic field is tangential around the wings of the remnant and continues beyond the visible part of the shell, nearly parallel to the Galactic plane.

Near to the west edge of G 5.4–1.2 lies a bright, edge-darkened compact source G 5.27–0.9. This source is connected to G 5.4–1.2 by a bridge of emission. The VLA image of G 5.27–0.9 by Frail & Kulkarni (1991) resolves a small protrusion at the west edge of this source into a comet-shaped nebula, stretching for about  $30''$  east of PSR B 1757–24 until it merges with the radio source G 5.27–0.9. The elongated nebula does not point back to the geometric centre of the SNR G 5.4–1.2 but misses it by about  $5'$  to the north (Frail et al. 1994).

The bright west wing of G 5.4–1.2 shows a trend of a steepening in the radio spectral index in either direction from the line drawn through the pulsar and the bridge of emission connecting the SNR with the radio source G 5.27–0.9 (Frail et al. 1994). The only available estimate of the spectral index for G 5.27–0.9,  $\alpha = +0.2$  (Caswell et al. 1987), suggests that the radio emission from this source is thermal. However, the detection of linear polarization in G 5.27–0.9 (Frail & Kulkarni 1991) indicates that the emission is rather non-thermal (see also Caswell et al. 1987). The radio emission of the comet-shaped nebula is characterized by a flat spectrum ( $\alpha \simeq 0$ ) and a high degree of polarization (Frail & Kulkarni 1991), and therefore is also non-thermal.

Optical observations of a field containing G 5.4–1.2 did not reveal any features related to the radio shell of this SNR (Zealey et al. 1979).

Recent *Chandra X-ray Observatory* observations of a  $4' \times 4'$  region of the west radio wing did not detect the X-ray emission from this part of the SNR’s shell, but they led to the discovery of an X-ray counterpart to the comet-shaped radio nebula associated with the pulsar (Kaspi et al. 2001). The length of the X-ray tail is  $\simeq 20''$ . It is likely that the tail X-ray emission is non-thermal.

The estimates of the age of the system are very uncertain. The maximum westward offset of the SN blast cen-

tre allowed by a model of G 5.4–1.2 and the upper limits on the pulsar westward motion (see Sect. 1) constrain the kinematic age of the system

$$t_{\text{kin}} \geq R_p/v_p^{\text{max}}. \quad (2)$$

Although, in principle,  $v_p$  could be as large as  $590 \text{ km s}^{-1}$ , in the following we adopt for  $v_p$  the maximum value allowed by the “worse” ( $2\sigma$ ) upper limit on the pulsar westward motion,  $v_p = 160 \text{ km s}^{-1}$ , to show that even in this “unfavourable” case the association between PSR B 1757–24 and G 5.4–1.2 could be real (in Sect. 4 we show, however, that the uncertainties in the pulsar transverse velocity do not affect the main conclusions of the paper). The kinematic age should be compared with the spin-down time-scale,

$$t_{\text{sd}} = \frac{2}{n-1} \left[ 1 - \left( \frac{P_0}{P} \right)^{n-1} \right] \tau, \quad (3)$$

where  $n$  is the braking index and  $P_0$  is the initial spin period. Note that all braking indices measured for young radio pulsars are less than 3. It is plausible that the braking index of PSR B 1757–24 is also less than 3 and therefore  $t_{\text{sd}} > \tau$  (provided that  $P_0 \ll P$ ): the smaller  $n$  the larger the discrepancy between  $t_{\text{sd}}$  and  $\tau$ .

For  $R_p = 23 d_5 \text{ pc}$  (Frail et al. 1994) and assuming that  $P_0 \simeq 0.5 \text{ ms}$  (i.e. the minimum spin period allowed by the neutron star stability), one has from (1), (2) and (3) that  $t_{\text{kin}} (\geq 9\tau) \simeq t_{\text{sd}}$  if  $n \leq 1.1$ , i.e. for the braking indices smaller than the smallest one ever measured for pulsars (cf. Thorsett et al. 2002). On the other hand, in the case of an off-centred cavity SN explosion  $R_p$  could be as small as  $\simeq 9 d_5 \text{ pc}$  (see Sect. 3.1). In this case  $t_{\text{kin}} (\geq 3.5\tau) \simeq t_{\text{sd}}$  if  $n \leq 1.6$  (for  $P_0 = 0.5 \text{ ms}$ ) or  $n \leq 1.4$  (for  $P_0 = 5 \text{ ms}$ ), i.e. for the indices comparable with the braking index measured for the Vela pulsar ( $n = 1.4 \pm 0.2$ ; Lyne et al. 1996).

Note also that  $n < 3$  is not the sole reason for the discrepancy between  $t_p$  and  $\tau$ . The true age of a pulsar could be larger than the characteristic spin-down age if the braking torque acting on the pulsar grows with time (e.g. due to the secular increase of the magnetic dipole moment; e.g. Blandford & Romani 1988) or is episodically enhanced (e.g. due to the interaction between the pulsar’s magnetosphere and the density inhomogeneities in the ambient medium; e.g. Gvaramadze 2001 and references therein).

In the following we assume that  $t_p = t_{\text{kin}} = 3.5\tau \simeq 5.4 \times 10^4 \text{ yr}$ .

The distance to the system PSR B 1757–24/SNR G 5.4–1.2 is also poorly constrained. The kinematic method suggests that the SNR is at a distance  $> 4.3 \text{ kpc}$  (Frail et al. 1994), while the Cordes & Lazio (2002) model for the Galactic electron density distribution gives the distance to the pulsar of  $\simeq 5.1 \pm 0.5 \text{ kpc}$ . Both estimates are not inconsistent with each other. In what follows we adopt a distance to the system of  $5 \text{ kpc}$ .

### 3. System PSR B 1757–24/SNR G 5.4–1.2: a scenario for the origin

We suggest that the origin of the system PSR B 1757–24/SNR G 5.4–1.2 is connected to a SN explosion within a bubble blown-up by the moving SN progenitor star during the Wolf-Rayet (WR) phase of its evolution. We also suggest that the SN blast centre was significantly offset towards the west edge of the bubble due to the proper motion of the SN progenitor, and that the SN blast wave was drastically decelerated by the interaction with a pre-existing massive wind-driven shell. These suggestions imply that PSR B 1757–24 was born close to the current position of the west edge of G 5.4–1.2, and that the distance traveled by the pulsar is much smaller than that allowed by the model of the SNR by Frail et al. (1994).

#### 3.1. Supernova progenitor and its processed ambient medium

Let us explain why we believe that the pre-SN was a WR star (i.e. the zero-age main-sequence (MS) mass of the SN progenitor was  $\geq 20 M_\odot$ ; e.g. Vanbeveren et al. 1998) and that the SN exploded within the WR bubble, but not in the bubble created during the preceding MS phase. In our reasoning we proceed from the fact that a young neutron star (born with a moderate kick velocity of appropriate orientation) can overrun the shell of the associated SNR only if: a) the SN exploded within a pre-existing bubble surrounded by a massive (see Sect. 3.2) shell; b) the SN explosion site was significantly offset from the centre of the bubble (e.g. Gvaramadze 2002a,b; cf. Shull et al. 1989; Arzoumanian et al. 2002). However, it is unlikely that these conditions can be fulfilled for the MS bubbles. Indeed, simple estimates show that massive stars (unless they are very massive and/or very slowly-moving) explode outside their MS bubbles (Brighenti & D’Ercole 1994). Moreover, the MS bubbles usually stall and their shells disappear well before the massive stars enter the subsequent evolutionary phases (Brighenti & D’Ercole 1994). On the other hand, if a massive star ended its evolution as a WR star, the energetic WR wind could create a new large-scale bubble, whose supersonic expansion drives a shell of swept-up interstellar matter during the relatively short WR phase. Besides, it is the short duration of the WR phase that implies that even a runaway massive star could explode within its WR bubble, while the stellar motion could cause a considerable offset of the SN blast centre from the centre of the bubble [see Fig. 4 of Gruendl et al. (2000) for a good illustration of this effect; see also Arnal (1992)].

The proper motion of the SN progenitor star causes it to escape from the bubble blown-up during the MS phase, so that the WR wind interacts directly with the unperturbed interstellar medium. The mass of the shell swept up by the end of the WR phase is  $M_{\text{sh}} = (4\pi/3)R_{\text{sh}}^3\rho_{\text{ISM}}$ , where  $R_{\text{sh}}$  is the radius of the shell,  $\rho_{\text{ISM}} = 1.3m_{\text{H}}n_{\text{ISM}}$ ,

$n_{\text{ISM}}$  is the number density of the ambient interstellar medium and  $m_{\text{H}}$  is the mass of a hydrogen atom. We stress that the (massive) wind-driven shell is a crucial ingredient of our scenario since it is the interaction of the SN blast wave with the shell that results in the abrupt deceleration of the blast wave and that, in turn, allows the pulsar born with a moderate kick velocity to overrun the SNR's shell. It is clear that the larger the mass of the shell the stronger the deceleration of the blast wave and the smaller the expansion velocity of the resulting SNR. To estimate  $M_{\text{sh}}$  we need to know  $n_{\text{ISM}}$  and  $R_{\text{sh}}$ .

The number density could be crudely evaluated by comparing the observed minimum size of the radio nebula ahead of the moving pulsar with the theoretically predicted one,

$$R_n = \kappa R_0 = \kappa(|\dot{E}|/4\pi c \rho_{\text{ISM}} v_p^2)^{1/2}, \quad (4)$$

where  $R_0$  is the stand-off distance,  $\kappa \simeq 1.26$  is a parameter which shows that the radio emission ahead of the pulsar comes from a layer of finite thickness of  $\simeq (\kappa - 1)R_0$  (Bucciantini 2002),  $|\dot{E}|$  is the spin-down luminosity of the pulsar and  $c$  is the speed of light; for the sake of simplicity we assumed here that the pulsar is moving in the plane of the sky and that the pulsar wind is isotropic. For  $R_n = 3.6 \times 10^{-2} d_5$  pc (Gaensler & Frail 2000) and  $|\dot{E}| \simeq 2.6 \times 10^{36} \text{ erg s}^{-1}$ , one has from Eq. (4) that  $n_{\text{ISM}} \simeq 1.0 \text{ cm}^{-3}$ .

Then we assume that at the moment of SN explosion the radius of the WR bubble/shell was  $R_{\text{sh}} = 20$  pc. For this value of  $R_{\text{sh}}$  and using the estimate of  $n_{\text{ISM}}$ , one has  $M_{\text{sh}} \simeq 10^3 M_{\odot}$ .

We also assume that the SN exploded near the west edge of the WR bubble (cf. Gvaramadze & Vikhlinin 2003, Gvaramadze 2003), on the line drawn through the tail behind the pulsar. In this case  $R_p \simeq 9 d_5$  pc, i.e. the SN blast centre is about  $6'$  east of the current position of the pulsar (or about  $3.5 d_5$  pc behind the west edge of the SNR G 5.4–1.2). Correspondingly,  $t_{\text{kin}} \simeq 5.4 \times 10^4 \text{ yr}$  ( $\simeq 3.5\tau$ ) (see Sect. 2). One can also estimate the peculiar velocity of the progenitor star,  $v_{\star} \simeq R_{\text{sh}}/t_{\text{WR}} \simeq 65 \text{ km s}^{-1}$ , where  $t_{\text{WR}} \simeq 3 \times 10^5 \text{ yr}$  is the duration of the WR phase (see, e.g., Vanbeveren et al. 1998), i.e. the SN progenitor was a runaway star (cf. Bandiera 1987). Note that the well-known runaway O-type star  $\zeta$  Pup has a similar peculiar velocity.

### 3.2. SNR G 5.4–1.2

Soon after the SN explosion the blast wave starts to interact with the closest (west) part of the shell, while in the opposite direction it freely expands through the low-density interior of the WR bubble until it collides with the shell. The further evolution of the blast wave depends on the mass distribution over the pre-existing shell. The SN blast wave becomes radiative if the shell column density (or the mass of the shell) exceeds a critical value.

There exist two main factors that affect the mass distribution over the shell. The first one is the large-scale den-

sity gradient in the ambient interstellar medium (usually oriented perpendicular to the Galactic plane). The role of this factor is obvious: the denser the ambient medium the larger the column density of the swept-up shell. The second factor is the large-scale interstellar magnetic field (at low Galactic latitudes it is nearly parallel to the Galactic plane). It causes transverse motions in the shell: the swept-up matter flows from the magnetic poles of the shell to the equator and thereby increases (up to ten times) the column density in this region of the shell (Ferrière et al. 1991). These factors naturally define the symmetry axes of the wind-driven shell (respectively, perpendicular and parallel to the Galactic plane) and later on those of the SNR (cf. Gvaramadze 1999, b). The inhomogeneous mass distribution over the shell results in that the SN blast wave first enters the radiative stage near the magnetic equator, that in turn results in the origin of an asymmetric and/or bilateral brightness distribution over the SNR's shell. Moreover, the reduced column density at the magnetic poles of the wind-driven shell results in the elongation of the SNR along the direction of the local large-scale interstellar magnetic field (see also Sect. 4).

The north-south elongation and the east-west brightness asymmetry of the SNR G 5.4–1.2 suggest that both aforementioned factors have an effect on this SNR and that the column density of the pre-existing wind-driven shell was maximum to the west<sup>1</sup>. The spectral index variations along the west wing of G 5.4–1.2 (see Sect. 2) also suggest that in this direction the SN blast wave encountered a region of enhanced (column) density [cf. Thorsett et al. (2002) and see references therein]. Therefore we expect that the expansion velocity of G 5.4–1.2 is minimum to the west.

To estimate the expansion velocity of the SNR one can use the results of numerical simulation of cavity SN explosions by Tenorio-Tagle et al. (1991), which showed that the SN blast wave merges with the pre-existing wind-driven shell, and the reaccelerated shell (now the SNR's shell) evolves into a momentum-conserving stage, if the mass of the shell is larger than about  $50M_{\text{ej}}$ , where  $M_{\text{ej}}$  is the mass of the SN ejecta. For any reasonable initial mass of the SN progenitor,  $M_{\text{ej}} \simeq 3.5 - 10 M_{\odot}$  (see Table 1 of Vanbeveren et al. 1998). Thus,  $M_{\text{sh}} > 50M_{\text{ej}}$  and the SNR G 5.4–1.2 is in the radiative stage<sup>2</sup>. The numerical simulations by Tenorio-Tagle et al. (1991) also showed that the reaccelerated shell acquires a kinetic energy  $E_{\text{kin}} = \beta E$ , where  $E = 10^{51} \text{ erg}$  is the SN energy and  $\beta \simeq 0.1$ . Thus, the initial expansion velocity of the SNR G 5.4–1.2 is  $\simeq (2\beta E/M_{\text{sh}})^{1/2} \simeq 100 \text{ km s}^{-1}$ . The westward expansion of the SNR, however, could be even slower due to the

<sup>1</sup> Note, however, that the asymmetric brightness of G 5.4–1.2 could also be caused by the proximity of the SN blast centre to the west edge of the pre-existing shell.

<sup>2</sup> This conclusion does not contradict the non-detection of optical emission from G 5.4–1.2 (see Sect. 2) in view of the large foreground obscuration towards this SNR (Caswell et al. 1987).

inhomogeneous mass distribution over the shell, so that the pulsar moving in the same direction with a velocity exceeding that of the SNR’s shell can easily overrun the SNR.

### 3.3. G 5.27–0.9

We now discuss the origin of the radio source G 5.27–0.9. We suggest that G 5.27–0.9 is a lobe of a low Mach number jet of gas outflowing from the interior of G 5.4–1.2 through the hole bored in the SNR’s shell by the escaping pulsar.

While the pulsar is moving through the shell of the SNR it creates a channel filled with hot, low-density gas of the SNR’s interior. After the pulsar overruns the SNR the gas starts to outflow through the hole in the shell and forms a supersonic jet. The gas velocity at the origin of the jet is  $v_j = [2(c_j^2 - c_{\text{ISM}}^2)/(\gamma - 1)]^{1/2} \simeq \sqrt{3} c_j$ , where  $c_j (>> c_{\text{ISM}})$  is the sound speed of the gas escaping from the SNR,  $c_{\text{ISM}}$  is the sound speed of the ambient interstellar medium and  $\gamma = 5/3$  is the specific heat ratio. The structure and the dynamics of supersonic jets propagating through the ambient medium are mainly determined by two parameters (measured at the origin of the jet): the jet Mach number,  $\mathcal{M}_j = v_j/c_j$ , and the jet to ambient medium density ratio,  $\rho_j/\rho_{\text{ISM}}$  (see Norman et al. 1982). It is clear that in our case  $\mathcal{M}_j \simeq 1.7$  and  $\rho_j/\rho_{\text{ISM}} \ll 1$ .

Numerical simulations conducted by Norman et al. (1982) showed that a low Mach number ( $\mathcal{M}_j \sim 1.5$ ) and low-density jet ends in a gradually inflating and slowly-moving lobe. The morphological similarity of this lobe (see Fig. 10a of Norman et al. 1982) and the radio nebula G 5.27–0.9 (see Fig. 1b of Frail & Kulkarni 1991) allows us to consider the existence of inner bright spots in G 5.27–0.9 and the edge-darkened appearance of this nebula (whose radio emission is likely due to the synchrotron losses of relativistic electrons accelerated at the internal shocks and those injected in the nebula by the pulsar) as indications that the jet has already reached its maximum spatial extent (see Norman et al. 1982). Therefore the pulsar moving along the jet axis was able to overrun the lobe and now it travels through the interstellar medium.

### 3.4. PSR B 1757–24 and its comet-shaped nebula

It is clear that the proper motion of a neutron star born in an off-centred cavity SN explosion could be oriented arbitrarily with respect to the geometric centre of the associated SNR (Gvaramadze 2002a,b; see also Bock & Gvaramadze 2002). Therefore one should not comment on why the comet-shaped nebula produced by PSR B 1757–24 does not point back to the geometric centre of the SNR G 5.4–1.2. We discuss some points related to the origin of this nebula.

The supersonic motion of PSR B 1757–24 through the interstellar medium results in the origin of an elongated structure, where the pulsar wind is swept back

by the ram pressure. The region occupied by the wind is bounded by a contact discontinuity, which asymptotically becomes cylindrical with a characteristic radius  $R \simeq 0.85 \mathcal{M}_p^{3/4} (1 - 0.85 \mathcal{M}_p^{-1/2})^{-1/4} R_0$ , where  $\mathcal{M}_p = v_p/c_{\text{ISM}}$  (Bucciantini 2002). For  $v_p = 160 \text{ km s}^{-1}$  and assuming that the temperature of the ambient interstellar medium is  $\simeq 8000 \text{ K}$ , one has  $R \simeq 6 R_0$  (or  $\simeq 7'' d_5^{-1}$ ), i.e. the value a few times larger than the half-width of the comet-shaped nebula. This implies that we see only a central (axial) part of a much wider region filled with the pulsar wind and that most of the pulsar wind is unobservable.

We suggest that the non-thermal X-ray emission of the cometary tail behind the pulsar is due to the synchrotron losses of the relativistic pulsar wind shocked at the termination shock, which extends in the tail up to a distance of  $L \simeq 1.29 \mathcal{M}_p R_0$  (see Bucciantini 2002 and Fig. 1 therein), and where the wind particles acquire non-zero pitch angles. Indirect support for this suggestion comes from the comparison of  $L \simeq 16 R_0$  or  $\simeq 19'' d_5^{-1}$  with the observed length of the X-ray tail of  $\simeq 20''$ .

We also suggest that the (non-thermal) radio emission of the comet-shaped nebula originates in the vicinity of the termination shock and in a much more extended narrow cylindrical region of subsonically moving shocked pulsar wind (cf. Bucciantini 2002). This suggestion implies that in the absence of the radio source G 5.27–0.9 the radio tail would be much longer than its X-ray counterpart [perhaps as long as the tail of the radio nebula “Mouse” (G 359.23–0.82; Yusef-Zadeh & Bally 1987) powered by the young pulsar PSR J 1747–2958 (whose spin characteristics are almost the same as those of PSR B 1757–24; Camilo et al. 2002)].

Finally, we note that the cometary morphology of the radio tail (the tail is wide close to the pulsar, then narrows, and then gradually widens again until it merges with G 5.27–0.9) could be interpreted as an indication that the magnetic field of the pulsar wind is responsible for the shaping of the pulsar wind nebula.

## 4. Discussion

We now show that the uncertainties in the pulsar velocity do not affect the main conclusions of the paper.

First, we consider the possibility that  $v_p$  could be larger than  $160 \text{ km s}^{-1}$  (see Sect. 1 and Sect. 2). Note that the larger  $v_p$  the smaller  $t_{\text{kin}}$  and the smaller the discrepancy between the latter and  $\tau$ . For  $v_p = 590 \text{ km s}^{-1}$  and  $R_p \simeq 9 \text{ pc}$  (Sect. 3), one has  $t_{\text{kin}} \simeq 1.50 \times 10^4 \text{ yr} \simeq \tau$ . On the other hand, the larger  $v_p$  the smaller  $n_{\text{ISM}}$  implied by Eq. (4) and the smaller  $M_{\text{sh}}$ . Therefore one can estimate the maximum value of  $v_p$  consistent with our suggestion that the SN blast wave becomes radiative after it encountered the pre-existing shell. For the minimum mass of the shell of  $\simeq 175 M_\odot$  (see Sect. 3.2), one has  $n_{\text{ISM}} \simeq 0.18 \text{ cm}^{-3}$  and  $v_p \simeq 380 \text{ km s}^{-1}$ . The latter estimate implies  $t_{\text{kin}} \simeq 2.2 \times 10^4 \text{ yr}$ , which is consistent with  $\tau$  if  $n \simeq 2.4$  (i.e. for the braking index compara-

ble with that of the Crab pulsar). Note, however, that for  $v_p = 380 \text{ km s}^{-1}$  the length of the termination shock  $L$  estimated in Sect. 3.4 is about 2 times larger than the observed length of the X-ray tail associated with PSR B 1757–54.

Second, one can consider the possibility that  $v_p < 160 \text{ km s}^{-1}$ . In this case, the smaller  $v_p$  the larger  $n_{\text{ISM}}$  and the larger  $M_{\text{sh}}$ . Let us assume that  $v_p = 120 \text{ km s}^{-1}$  (cf. Thorsett et al. 2002). From (4) one has that  $n_{\text{ISM}} = 1.8 \text{ cm}^{-3}$ , that corresponds to  $M_{\text{sh}} \simeq 1.5 \times 10^3 M_{\odot} \gg 50 M_{\text{ej}}$ , i.e. the SNR is in the radiative stage. The only “unpleasant” consequence of the reduction of  $v_p$  is the increase of  $t_{\text{kin}}$ . However, for  $R_p = 9 \text{ pc}$ , one has that  $t_{\text{kin}} (\simeq 4.7\tau) \simeq t_{\text{sd}}$  if  $n < 1.4$  (for  $P_0 = 0.5 \text{ ms}$ ) or  $n < 1.2$  (for  $P_0 = 5 \text{ ms}$ ), i.e. for the braking indices still comparable with that of the Vela pulsar (recall that the assumption that  $n < 3$  is not the only way to reconcile  $t_{\text{kin}}$  and  $\tau$ ).

In conclusion we discuss an issue related to our suggestion that PSR B 1757–24 and the SNR G 5.4–1.2 are the remnants of a SN explosion within a bubble blown-up by the moving SN progenitor star during the WR phase of its evolution. Namely we briefly discuss the origin of elongated axisymmetric SNRs (e.g. G 3.7–0.2, G 16.2–2.7, G 296.5+10.0, G 332.4–0.4, G 356.3–1.5), constituting a subclass of the more general class of bilateral SNRs (e.g. Kesteven & Caswell 1987).

Recently Gaensler (1998) demonstrated that the bilateral SNRs show a generic tendency to be aligned with the local large-scale Galactic magnetic field. This tendency implies that the regular interstellar magnetic field is responsible not only for the bilateral symmetry of these SNRs, but also for the elongated shape of some of them. On the other hand, it is known that the tension associated with the interstellar magnetic field cannot directly affect the shape of a typical SN blast wave to cause it to be elongated (e.g. Manchester 1987). To explain the origin of elongated SNRs, Gaensler (1998) suggested that the SN blast waves in these SNRs take on the shape of wind bubbles blown-up by the SN progenitor stars during the MS phase and distorted by the surrounding (regular) magnetic field (cf. Arnal 1992). A main concern with this suggestion is that the majority of massive stars explode outside their MS bubbles (see Sect 3.1). In principle, one cannot exclude that the progenitors of some elongated SNRs were very slowly-moving massive stars. But even in this case the stellar motion results in a significant offset of the SN blast centre from the centre of the MS bubble (for  $v_{\star} = 1 \text{ km s}^{-1}$  and  $t_{\text{MS}} \simeq 10^7 \text{ yr}$ , this offset is  $\simeq 10 \text{ pc}$ ). Therefore, it is likely that at least two elongated bilateral SNRs (G 296.5+10.0 and G 332.4–0.4) with centrally located stellar remnants have a different origin.

We propose that the elongated axisymmetric SNRs are the diffuse remnants of SNe that exploded within WR bubbles surrounded by magnetized wind-driven shells. As we already mentioned in Sect. 3.2, the regular ambient magnetic field modifies the structure of wind-driven shells in such a way that the density distribution over the shell acquires an axial symmetry with the minimum column

density at the magnetic poles. Thus the origin of elongated axisymmetric SNRs could be attributed to the interaction of the SN blast wave with a pre-existing axisymmetric WR shell, whose orientation with respect to the Galactic plane is determined by the orientation of the local large-scale interstellar magnetic field [see Fig. 1, 4 and 6 of Gruendl et al. (2000) for several examples of axisymmetric shells created by WR stars; note that these shells are aligned nearly parallel to the Galactic plane]. Our proposal implies that at least some progenitors of SNe resulting in the origin of elongated axisymmetric SNRs are massive stars that ended their evolution as WR stars. The detailed analysis of this problem will be presented elsewhere.

## 5. Summary

We have proposed a scenario for the origin of the system PSR B 1757–24/supernova remnant G 5.4–1.2 based on the suggestion that both objects are the remnants of a supernova that exploded within a pre-existing bubble blown-up by a runaway massive star (the supernova progenitor) during the final (Wolf-Rayet) phase of its evolution. Our suggestion implies that (a) the supernova blast centre was significantly offset from the geometric centre of the wind-blown bubble (i.e. from the centre of the future supernova remnant), (b) the bubble was surrounded by a massive wind-driven shell, and (c) the supernova blast wave was drastically decelerated by interaction with the shell. Therefore one can understand how the relatively young and low-velocity pulsar PSR B 1757–24 was able to escape from the associated supernova remnant G 5.4–1.2 and why the inferred vector of pulsar transverse velocity does not point away from the geometric centre of the remnant. A possible origin of the radio source G 5.27–0.9 (located between PSR B 1757–24 and G 5.4–1.2) was proposed. It has been suggested that this nebula is a lobe of a low Mach number ( $\simeq 1.7$ ) jet of gas outflowing from the interior of G 5.4–1.2 through the hole bored in the shell of this supernova remnant by the escaping pulsar. We have discussed the origin of the comet-shaped pulsar wind nebula and suggested that the non-thermal emission of this nebula originates in the vicinity of the termination shock and in the cylindric region of subsonically moving shocked pulsar wind. We also discussed the origin of elongated axisymmetric supernova remnants and suggested that they are the diffuse remnants of supernova explosions within pre-existing Wolf-Rayet bubbles surrounded by axisymmetric shells, whose axes of symmetry are aligned parallel to the local large-scale interstellar magnetic field.

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## References

Arnal, E.M. 1992, A&A, 254, 305

- Arzoumanian, Z., Chernoff, D.F., & Cordes, J.M. 2002, *ApJ*, 568, 289
- Bandiera, R. 1987, *ApJ*, 319, 885
- Blandford, R.D., & Romani, R.W. 1988, *MNRAS*, 234, 57p
- Bock, D.C.-J., & Gvaramadze, V.V. 2002, *A&A* 394, 533
- Brighenti F., & D’Ercole A. 1994, *MNRAS*, 270, 65
- Bucciantini, N. 2002, *A&A*, 387, 1066
- Camilo, F., Manchester, R.N., Gaensler, B.M., & Lorimer, D.R. 2002, *ApJ*, 579, L25
- Caswell, J.L., Kestenev, M.J., Komesaroff, M.M., et al. 1987, *MNRAS*, 225, 329
- Cordes, J.M., & Lazio, T.J.W. 2002, astro-ph/0207156 (see also <http://rsd-www.nrl.navy.mil/7213/lazio/ne-model>)
- Ferrière, K.M., Mac Low, M.-M., & Zweibel, E.G. 1991, *ApJ*, 375, 239
- Frail, D.A., & Kulkarni, S.R. 1991, *Nat*, 352, 785
- Frail, D.A., Kassim, N.E., & Weiler, K.W. 1994, *ApJ*, 107, 1120
- Gaensler, B.M. 1998, *ApJ*, 493, 781
- Gaensler, B.M., & Frail, D.A. 2000, *Nat*, 406, 158
- Gruendl, R.A., Chu, Y.-H., Dunne, B.C., & Points, S.D. 2000, *AJ*, 120, 2670
- Gulliford, P. 1974, *Ap&SS*, 31, 241
- Gvaramadze, V.V. 1999, *Odessa Astron. Publ.*, 12, 117
- Gvaramadze, V.V. 2001, *A&A*, 374, 259
- Gvaramadze, V.V. 2002a, in *ASP Conf. Ser.* 271, *Neutron Stars in Supernova Remnants*, eds. P.O.Slane, & B.M.Gaensler (San Francisco: ASP), 23
- Gvaramadze, V.V. 2002b, in *New Visions of the X-ray Universe in the XMM-Newton and Chandra Era*, ed. F.Jansen, ESA SP-488, in press [astro-ph/0208028]
- Gvaramadze, V.V. 2003, in *High Energy Processes and Phenomena in Astrophysics*, IAU Symp. 214, eds. X.D. Li, V. Trimble, & Z.R. Wang, in press [astro-ph/0212541]
- Gvaramadze, V.V., & Vikhlinin, A.A. 2003, *A&A*, 401, 625
- Kaspi, V.M., Gotthelf, E.V., Gaensler, B.M., & Lyutikov, M. 2001, *ApJ*, 562, L163
- Kestenev, M.J., & Caswell, J.L. 1987, *A&A*, 183, 118
- Kompaneets, A. 1960, *Sov. Phys. Dokl.*, 5, 46
- Lyne, A.G., Pritchard, R.S., Graham-Smith, F., & Camilo, F. 1996, *Nat*, 381, 497
- Manchester, R.N. 1987, *A&A*, 171, 205
- Manchester, R.N., D’Amico, N., & Tuohy, I.R. 1985, *MNRAS*, 212, 975
- Manchester, R.N., Kaspi, V.M., Johnston, S., Lyne, A.G., & D’Amico, N. 1991, *MNRAS*, 253, 7p
- Milne, D.K., Caswell, J.L., & Haynes, R.F. 1992, *MNRAS*, 255, 707
- Norman, M.L., Smarr, L., Winkler, K.-H.A., & Smith, M.D. 1982, *A&A*, 113, 285
- Shull, J.M., Fesen, R.A., & Saken, J.M. 1989, *ApJ*, 346, 860
- Tenorio-Tagle, G., Różyczka, M., Franco, J., & Bodenheimer, P. 1991, *MNRAS*, 251, 318
- Thorsett, S.E., Briskin, W.F., & Goss, W.M. 2002, *ApJ*, 573, L111
- Vanbeveren, D., De Loore, C., & Van Rensbergen, W. 1998, *A&AR*, 9, 63
- Yusef-Zadeh, F., & Bally, J. 1987, *Nat*, 330, 455
- Zealey, W.J., Elliot, K.H., & Malin, D.F. 1979, *A&AS*, 38, 39